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Patterns of Femoral Bone Remodeling Dynamics in a Medieval Nubian Population

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KEY WORDS osteon; Haversian canal; remodeling; stress; Nubia

ABSTRACT The relationship between age, sex and histomorphometry in femoral cortical bone was examined in a skeletal population of late Medieval antiquity (AD 1250–1450) from Kulubnarti, in Sudanese Nubia. These skeletal remains are naturally mummified and in an excellent state of preservation. The study sample consisted of femoral cross sections from 24 females and 19 males ranging in age from 20 to 50+ years.

Femoral cross sections were examined using an image analysis system. Numbers of secondary osteons and osteon fragments were counted, osteon area and Haversian canal area were measured, and several variables were calculated to assess differences between sexes and among age groups in bone remodeling variables.

The results indicate significant differences between the sexes in osteon number and size. Males had significantly more intact osteons than females, whereas females had significantly larger osteons than males. Haversian canal dimensions were not statistically significant between the sexes. Sex differences in activity patterns in which males were involved in more physically strenuous tasks may have contributed to differences in remodeling variables.

Interpopulational comparisons suggest that mechanical strain affects the microstructural features examined in this study. In particular, small Haversian canals in some archaeological skeletal populations are associated with higher bone volume, which may result from high levels of mechanical strain. Am J Phys Anthropol 104:133–146, 1997.

Since their excavation in 1979, human remains from the Medieval site of Kulubnarti (Fig. 1) have been the focus of a host of analyses aimed at reconstructing the biocultural adaptation of this ancient Nubian community. Because the remains were naturally mummified in a climate receiving less than 1 mm of rain on average per year, it has been possible to apply both microscopic and macroscopic techniques to the phenomena of bone growth and development, cortical bone maintenance and loss as well as other age-related degenerative changes of the skeleton. This evidence has, in turn, provided important insights into health and adaptation of the Kulubnarti people. The present research investigates the relationship between age, sex and the histomorphometry of compact bone and is based on a growing body of evidence that activity patterns and the organization of bone tissue are inexorably linked.

The purpose of this study is to assess bone remodeling variables, including intact and fragmentary osteon number, osteon area, Haversian canal area, osteon population density, accumulated osteon creations, percent osteonal refilling and net osteonal remodel-

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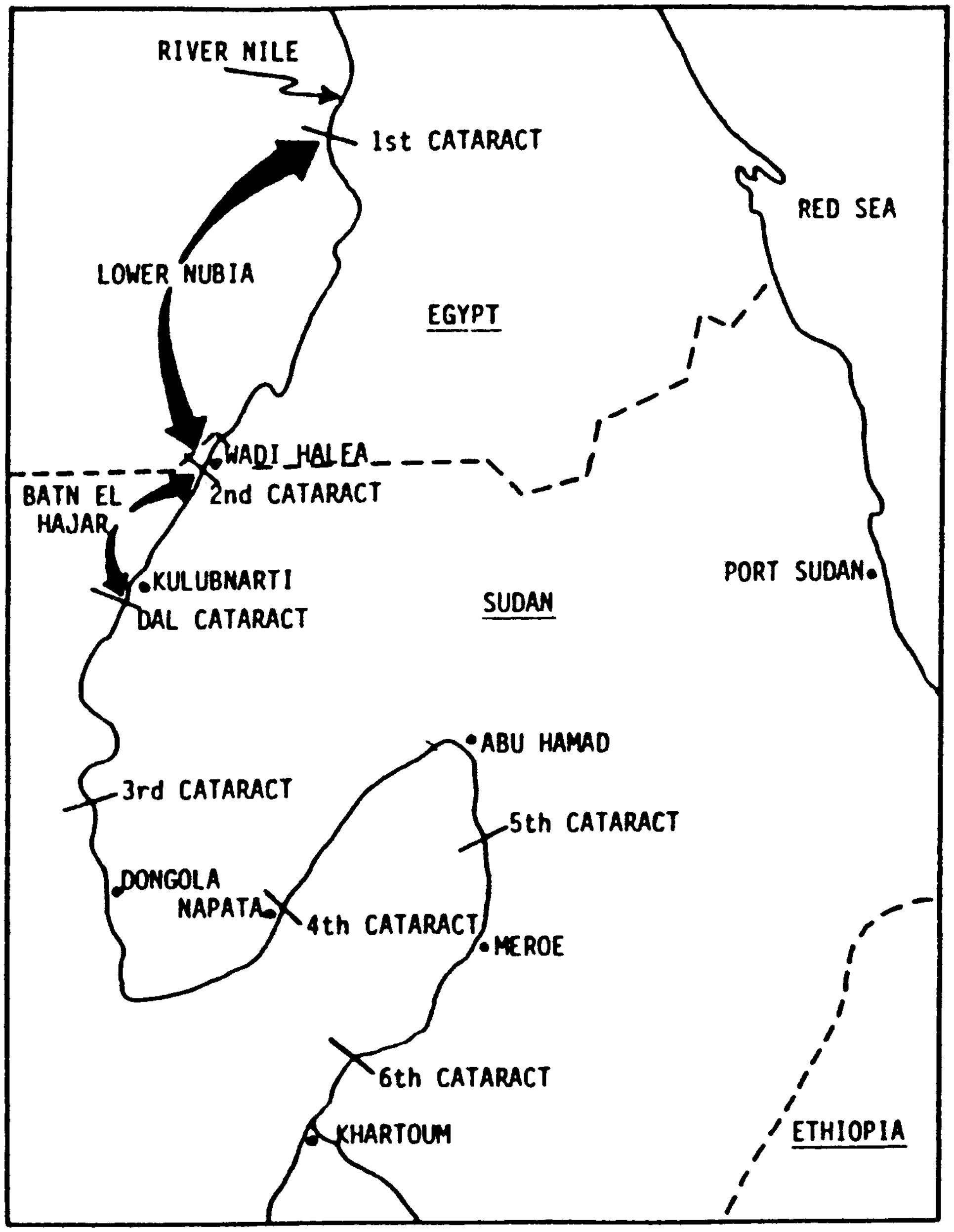

Fig. 1. Map of Nubia.

ing and their relationship to sex and age for an archaeological population from Kulubnarti, Nubia, of late Medieval antiquity (AD 1250–1450). The results of this analysis are analyzed in light of archaeological and ethnographic evidence for mechanical stress that affected Nubia's ancient population. Comparisons of microstructural measurements, age and sex are made between the results obtained by this study and the results obtained by other researchers, including studies of modern samples (Currey, 1964; Thompson, 1980; Stout and Lueck, 1995), another ancient Nubian sample (Martin, 1983), an

archaic Native American sample (Burr et al., 1990) and a fossil hominid sample (Abbott et al., 1996). These comparisons are used to identify differences in histomorphometry related to activity pattern, particularly the effects of mechanical stress.

Human bone has been studied for decades at both the macroscopic and microscopic levels. Early macroscopic studies conducted on modern samples primarily focused on changes in cortical thickness to document bone loss. For example, Bartley and Arnold (1967) documented a modern pattern of decreased cortical thickness with age in 112 cadavers, which showed that males and females lose bone at different rates, with females losing bone at a much higher rate than males.

Early clinical microscopic studies of human bone histology largely focused on patterns of change in bone with age. Kerley (1965) used these patterns to develop a method of age determination. He did this by counting the total number of secondary osteons, osteon fragments and non-Haversian canals and estimating the percentage of unremodeled lamellar bone remaining in long bones. Subsequent studies were directed toward refining this technique (Ahlquest and Damsten, 1969; Singh and Gunberg, 1970; Eriksen, 1991).

Macroscopic studies of bone loss were also conducted on ancient populations, and proved to be important for distinguishing differences in bone biodynamics which may be influenced by genetics or the environment. Dewey et al. (1969) studied the relationship between cortical thickness, age and sex of a sample of femoral sections taken from the skeletal remains of 203 adults representing three time periods (ranging from 350 BC to AD 1300) from Wadi Halfa, Sudan (ancient Nubia). Previous research on the dentition of these populations by Greene et al. (1967) showed that although they were separated temporally, they were genetically continuous. Dewey and colleagues found differences within this sample between males and females. Specifically, they reported that Nubian males maintained their cortical bone until age 50 and then they began to experience cortical thinning. Females, however, showed significant cortical bone loss with age ($P < 0.05$), beginning at age 20, and were therefore experiencing pre- and postmenopausal osteopenia. In Dewey's study, this trend was attributed to a combination of poor calcium intake and extended lactation.

Studies linking bone loss and health have also been conducted on a microscopic level. For example, Martin and Armelagos (1979) studied part of the sample originally studied by Dewey from Wadi Halfa dating from 350 BC to AD 350. Microradiographs of femoral thin sections from 74 adults were analyzed to determine cortical thickness, bone formation rate and bone resorption rate. Martin and Armelagos (1979), like Dewey et al. (1969), observed significant bone loss with age in females ($P < 0.05$). In addition, females in the third decade had significantly more resorption spaces and forming osteons than their male counterparts ($P < 0.05$). This suggested a slower rate of mineralization in females from 20 to 29 years of age than in males from the same age category. The authors concluded that the severe bone loss observed in third decade females was probably the result of chronic nutritional stress in addition to stresses of pregnancy and lactation.

Histomorphometric studies have also identified links between bone microstructure and mechanical stress. Both high osteon population density (OPD) and large osteon size improve the fatigue properties of bone. Specifically, high OPD inhibits the growth of microcracks initiated by cyclic loading of bone (Martin and Burr, 1989). In addition, it requires more force to fatigue bone when osteons are greater than 200 µm in diameter (Corondan and Haworth, 1986).

In a study of the femoral cortex of 55 individuals from a 14th to 19th century Pecos Indian population, Burr et al. (1990) found that males had a significantly higher OPD than females ($P < 0.06$), but that females had significantly larger osteon areas than males ($P < 0.02$). Both a high OPD and large osteon area are consistent with the intense physical activity this population was experiencing. Further, both Pecos males and females had Haversian canals that were about half the size of those observed in modern samples. Because osteon areas were

within the range those observed in modern samples, Burr and colleagues concluded that small Haversian canal areas in the Pecos Indians may also represent an adaptation to high levels of biomechanical stress, because the result is an increase in bone volume.

The Kulubnarti sample provides an opportunity to expand on Burr et al.'s (1990) investigation, particularly because it represents another population that experienced high levels of mechanical stress. The differences observed in osteon area between males and females in the Pecos Indians are not characteristic of modern populations and it is unclear whether this characteristic of other human groups. One possibility is that most modern populations do not experience enough physical stress to cause such a response. Analysis of another ancient population, therefore, may shed some light on this question.

Previous research conducted on the Kulubnarti population has demonstrated a clear pattern of mechanical stress. This research make great sense given the setting of the population. Kulubnarti is an island located in the southern extreme of the *Batn el Hajar* ("belly of rock") of Upper Nubia (Fig. 1). The harsh landscape of this location, characterized by extremely rocky and rugged terrain, is described by Adams (1977:26) as "the most barren and forbidding of all Nubian environments."

Populations in this region lived in small-scale farming villages and practiced agriculture made possible by irrigation using a water wheel, or *saquia*, and by retaining walls which protected alluvial soils from floods (Van Gerven et al., 1990). Subsistence in Kulubnarti was always marginal due to the harsh environmental conditions. Archaeological evidence shows that the staple crops included sorghum, millet, barley, beans, lentils, peas, dates and wheat. Cattle, sheep and pigs were a source of some protein (Van Gerven et al., 1990).

The terrain and harsh conditions in Nubia undoubtedly contributed to physical stress in the population. Studies of fractures provide evidence for a very active lifestyle (Burrell, 1986; Kilgore et al., in press). These studies documented a very high rate of fracture and traumatic lesions in long bones. Of the 146 adult individuals examined by Kilgore and Van Gerven, 32.9% had healed fractures, which is a high percentage compared to other populations. Both studies revealed that the highest fracture rate was in the upper limbs, a feature which is probably related to a high frequency of falls on rough terrain.

A study conducted by Kilgore (1984) on degenerative joint disease is consistent with a population enduring intense physical stress. Osteoarthritis and osteophytosis were analyzed in 136 adult individuals. The degenerative lesions identified in this study increased significantly with age and were partially attributed to tasks such as traversing rough terrain and climbing steep riverbanks. In addition, males had higher frequencies of osteophyte formation than females. Kilgore observed overlap between the Kulubnarti populations and other populations in vertebral joint degeneration, which she attributed to bipedal locomotion. Kilgore observed considerable differences in non-vertebral joint degeneration between the Kulubnarti populations and other populations, however, which she concluded were the result of cultural differences in activity patterns, particularly subsistence tasks.

Ethnographic observations based on the people inhabiting this region today have shown that patterns of mechanical stress continue into the modern day (Van Gerven, personal communication). Agriculture is still the major source of subsistence, although now modern pumps are used to obtain water for irrigation. In modern Nubia, both men and women are involved in physical labor, but males are responsible for the heavy labor associated with clearing the fields and women are responsible for the more time consuming but lighter tasks of maintaining fields and tending to livestock.

The terrain and activity patterns at Kulubnarti combined to provide a physically stressful environment. Previous research on degenerative joint changes and fractures has shown that the population was physically affected by such harsh conditions. Histomorphometry of the Kulubnarti population is analyzed in the light of the evidence for mechanical stress.

MATERIALS AND METHODS

The skeletal sample chosen for this study is from a late Medieval (AD 1250–1450) cemetery at Kulubnarti, located near the Dal Cataract in Sudanese Nubia (Fig. 1). These remains are excellently preserved because Nubia experiences less than 1 mm of rain per year, so in many cases, the remains have undergone the process of natural mummification.

The study sample consists of femoral cross sections from 43 adult individuals (19 male, 24 female), aged 20 to 51+ years at age of death. The age and sex distribution of this sample is illustrated in Table 1. Sex was determined for these individuals using pelvic morphology and soft tissue, including presence of genitals and facial hair when possible. For age estimation, remains were seriated using multiple indicators including *os pubis*, degenerative joint changes, ectocranial suture closure and dental attrition (Van Gerven et al., 1981).

The femoral cross sections used for this study were removed from the midpoint of the femoral diaphysis and prepared by Prendergast-Moore (1987). After removal, the sections were ground by hand to a thickness of 100–150 µ. The sections were stained with Osteochrome Villanueva Bone Stain (no. 16280, Polysciences, Inc.) and mounted on microslides using Permount histological mounting medium.

Eight sites were used for microscope field locations (Fig. 2), including four sites along the axis of linea aspera (two periosteal and two endosteal) and four sites perpendicular to the axis of linea aspera. Each field was examined using an E Licht Company compound light microscope and Cue-2 Olympus Image Analyzer software (Galai, 1991). First, the numbers of intact secondary osteons and osteon fragments were counted for each field (2.5 mm^2 each, 20 mm^2 total) at 40× magnification. Stout (1978) recommends counting at least 200 osteons per slide and since Martin (1983) reported counting approximately 25 osteons per 2.5 mm^2 field, analysis of eight fields resulted in counts around 200 osteons. The borders of each field were defined on the monitor by superimposing a computer-generated grid.

TABLE 1. Sex, age distribution, and mean age of sample population

Age	Females	Males	Combined
20–29 years	6	6	12
30–39 years	6	6	12
40–49 years	6	6	12
50+ years[1]	6	1	7
Total	24	19	43
Mean age	38.7	35.5	37.2

[1]It is important to note that only one male represents the 50+ age category, but data collected for this individual and used for comparisons.

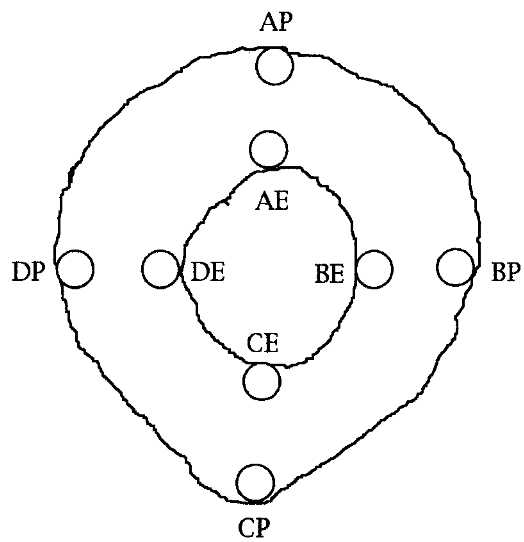

Fig. 2. Location of microscope fields.

At 100× magnification, the dimensions of 10 osteons were measured at each site. Two measurements were taken for each osteon, including Haversian canal area (HCA) and osteon area (OA). Area measurements were taken by simply tracing the structure (canal or osteon) with a stylus and then producing computer calculated measurements.

Ten variables were counted, measured or calculated based on methods outlined by Frost and Wu (1967), Wu et al. (1970), Stout and Teitelbaum (1976), Frost (1987a) and Stout and Paine (1994).

1. Intact Osteon Density (IO): number of complete osteons per square millimeter (a complete osteon is one in which at least 90% of the Haversian canal is unremodeled).

2. Fragmentary Osteon Density (FR): number of fragmentary osteons per square millimeter (a fragmentary osteon is one in

which 10% or more of the Haversian canal has been remodeled).

3. Haversian Canal Area (HcA): average area of Haversian canals, based on measurements of 80 canals per individual.

4. Osteon Area (OA): average area of osteons (including their Haversian canals), based on measurements of 80 osteons per individual.

5. Mean Osteonal Cross Sectional Area (A_h): average area of bone per complete secondary osteon (bone between the cement line and Haversian canal), based on an average cross sectional area of 80 osteons per femur. This variable was calculated using the following formula:

$$A_h = OA - HcA$$

6. Mean Cross Sectional Diameter (D_h): diameter of complete osteons, calculated using the mean osteonal cross sectional area:

$$D_h = (4A_h/\pi)^{-2}$$

7. Osteon Population Density (OPD): total number of intact and fragmentary osteons, calculated using the following formula:

$$OPD = IO + FR$$

8. Accumulated Osteon Creations (AOC): total number of intact, fragmentary and missing osteons for a given OPD, calculated using the following formula:

$$AOC = IO + FR + \text{Missing Osteons}$$

Missing osteons are old osteons that have been completely replaced by new osteons and are therefore no longer visible. The number of missing osteons increases with age until an asymptote is reached, when each new osteon creation removes evidence of an earlier osteon creations. Frost (1987a) provided a new method for estimating missing osteons that was later validated by Stout and Paine (1994) on an autopsy sample. The algorithm used to account for missing osteons uses a scaling operator, β, which can be multiplied by OPD to estimate AOC. β is the AOC/OPD ratio and can be calculated using the following formula:

$$\beta = (1 - a^x)^{-1}$$

where a = OPD normalized to its predicted asymptote, or:

$$a = OPD\,(OPD\ \text{asymptote})^{-1}$$

and x = 3.5, according to Frost's (1987a) analysis of previously published data. The OPD asymptote can be estimated for each specimen using the following formula:

$$OPOD\ \text{asymptote} = k[(D_h)^2]^{-1}$$

where Dh = mean cross sectional diameter and k = a fragmentary osteon packing factor that accounts for a higher number of intact plus fragmentary osteons than can be predicted based on a theoretical limit of intact osteons alone; k can be calculated using the following formula:

$$k = (OPD\ \text{asymptote})(D_h)^2$$

A value of 1.38 was used for k. This value was reported by Abbott et al. (1996) to be appropriate for the femur because the asymptote is about 30/mm^2.

9. Net Osteonal Remodeling (net $V_{f,r,t}$): total amount of remodeling that occurred over an individual's lifetime, which can be calculated using the following formula:

$$\text{net } V_{f,r,t} = (AOC)(A_h)$$

This formula is particularly important because it does not depend on chronological age or the effective age of the adult compacta. Activation frequency and bone formation rate cannot currently be calculated for the femur because the effective age of the adult compacta is unknown.

10. Percent Osteonal Refilling (%OR): amount of bone per osteon replaced by osteoblasts removed by osteoclasts, calculated using the following formula:

$$\%OR = (OA - HcA)/OA$$

The variables assessed were compared between sexes and among age categories using multi-way analysis of variance tests (MANOVA). Comparisons with published data were made using Student's *t*-tests.

RESULTS

Age differences

Table 2 shows osteon counts and area measurements by age category and sex and

TABLE 2. Intact osteons (IO), fragmentary osteons (FR), Haversian canal area (HcA), osteon area (OA), mean osteonal cross sectional area (A_h) and mean osteonal cross sectional diameter (D_h) by age and sex in the femur

Sex	Age (years)	IO (n/mm²)	FR (n/mm²)	HcA (mm²)	OA (mm²)	A_h (mm²)	D_h (mm)
F	20–29	5.76 ± 0.41	3.68 ± 0.57	0.0020 ± 0.0001	0.042 ± 0.003	0.040 ± 0.003	0.224 ± 0.009
	30–39	8.07 ± 0.67	4.33 ± 0.56	0.0023 ± 0.0003	0.039 ± 0.003	0.037 ± 0.003	0.215 ± 0.007
	40–49	7.12 ± 0.50	4.85 ± 0.22	0.0020 ± 0.0002	0.040 ± 0.002	0.038 ± 0.002	0.218 ± 0.007
	50+	5.96 ± 0.37	5.86 ± 0.44	0.0020 ± 0.0001	0.040 ± 0.002	0.038 ± 0.001	0.220 ± 0.004
M	20–29	8.73 ± 0.58	2.54 ± 0.24	0.0020 ± 0.0002	0.037 ± 0.003	0.035 ± 0.003	0.211 ± 0.009
	30–39	10.68 ± 0.62	2.74 ± 0.33	0.0026 ± 0.0006	0.037 ± 0.004	0.034 ± 0.003	0.207 ± 0.009
	40–49	9.88 ± 0.77	2.50 ± 0.25	0.0021 ± 0.0004	0.035 ± 0.002	0.033 ± 0.002	0.205 ± 0.006
	50+	9.36 ± N/A	2.48 ± N/A	0.0021 ± N/A	0.031 ± N/A	0.029 ± N/A	0.191 ± N/A

Values are the mean ± S.E.

TABLE 3. Osteon population density (OPD), accumulated osteon creations (AOC), net osteonal remodeling (net $V_{f,r,t}$) and percent osteonal remodeling (%OR) by age and sex in the femur

Sex	Age (years)	OPD (n/mm²)	AOC (n/mm²)	net $V_{f,r,t}$ (mm²/mm²)	%OR
F	20–29	9.28 ± 0.54	10.03 ± 1.77	0.402 ± 0.047	95.08 ± .11
	30–39	12.39 ± 0.97	13.01 ± 1.05	0.465 ± 0.025	94.03 ± .80
	40–49	11.96 ± 0.66	12.63 ± 0.80	0.474 ± 0.039	94.72 ± .43
	50+	11.81 ± 0.74	12.44 ± 0.88	0.469 ± 0.029	94.93 ± .13
M	20–29	11.27 ± 0.61	11.64 ± 0.65	0.404 ± 0.030	94.63 ± .44
	30–39	13.42 ± 0.61	14.12 ± 0.62	0.473 ± 0.038	93.05 ± .78
	40–49	12.32 ± 0.78	12.73 ± 0.83	0.414 ± 0.019	94.18 ± .56
	50+	11.84 ± N/A	12.04 ± N/A	0.344 ± N/A	93.10 ± N/A

Values are the mean ± S.E.

calculated variables are shown in Table 3. As shown in Figure 3, the number of intact osteons (IO) differs with age significantly ($P < 0.01$). For both males and females, the number of intact osteons increases from the third decade to the fourth decade and then decreases until the sixth decade. In females, intact osteons increase from 5.76/mm^2 to 8.07/mm^2 and then decrease to 5.96/mm^2. In males, the number of intact osteons increases from 8.73/mm^2 to 10.68/mm^2 and then decreases to 9.36/mm^2.

Changes in the number of fragmentary osteons (FO) with age are depicted in Figure 4. Only females show significant differences with age ($P < 0.05$). The number of fragmentary osteons in females increases with age from 3.68/mm^2 during the third decade to 5.86/mm^2 during the sixth decade.

As shown in Table 2 and Figures 5 and 6, osteonal dimensions, including Haversian canal area (HcA), osteon area (OA), mean osteonal cross sectional area (A_h) and mean osteonal cross sectional diameter (D_h) do not show statistically significant differences with age.

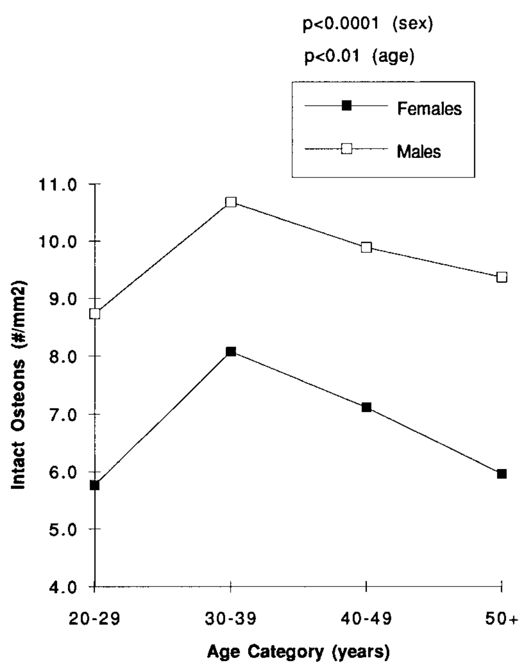

Fig. 3. Number of intact osteons by age category for females and males.

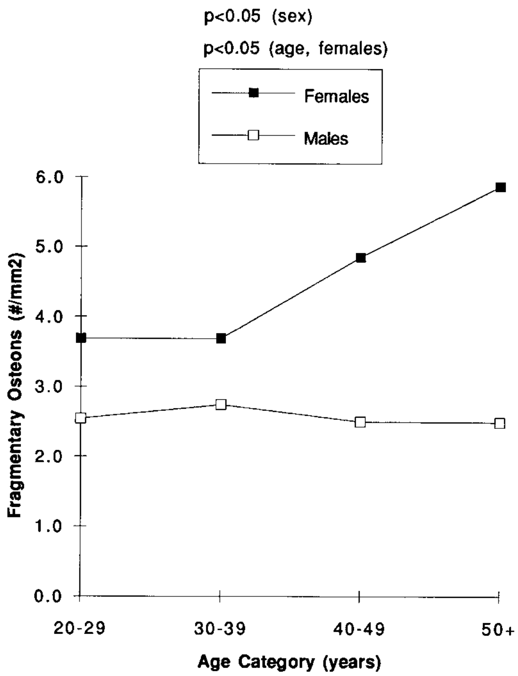

Fig. 4. Number of fragmentary osteons by age category for females and males.

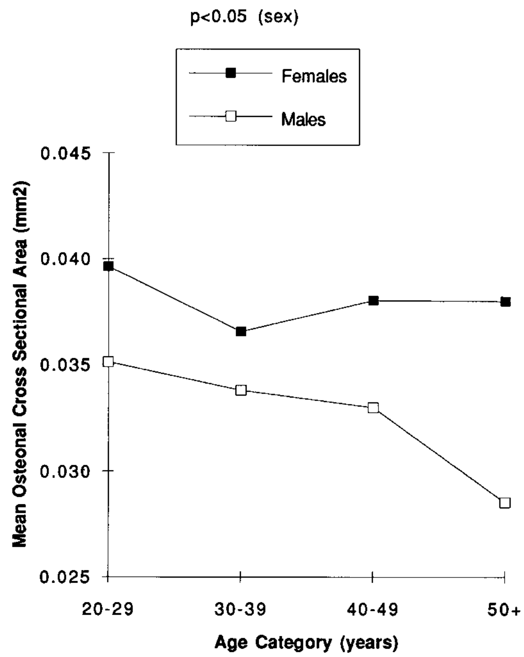

Fig. 6. Mean osteonal cross sectional area by age category for females and males.

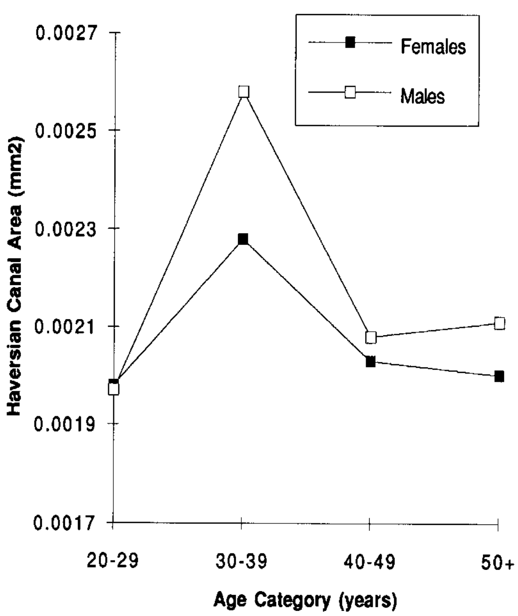

Fig. 5. Haversian canal area by age category for females and males.

Osteon population density (OPD) differs significantly by age (Table 3, Fig. 7). Both males and females exhibit an increase in OPD from the third to the fourth decades and then a decrease until the sixth decade. In females, it increases from 9.28/mm^2 to 12.39/mm^2 and then decreases to 11.81/mm^2. Males show an increase from 11.27/mm^2 to 13.42/mm^2 and then a decrease to 11.84/mm^2.

Changes in accumulated osteon creations (AOC) with age are shown in Table 3 and Figure 8. AOC differs significantly with age ($P < 0.02$). Both sexes show the same pattern of increase and subsequent decrease observed for OPD. In females, AOC increases from 10.03/mm^2 in the third decade to 13.01/mm^2 in the fourth decade and then decreases to 12.44/mm^2 in the sixth decade. Male AOC increases from 11.64/mm^2 during the third decade to 14.12/mm^2 and then decreases to 12/04/mm^2 in the sixth decade.

Net osteonal remodeling (net $V_{f,r,t}$) and percent osteonal refilling (%OR) are shown in Table 3 and Figures 9 and 10. No statisti-

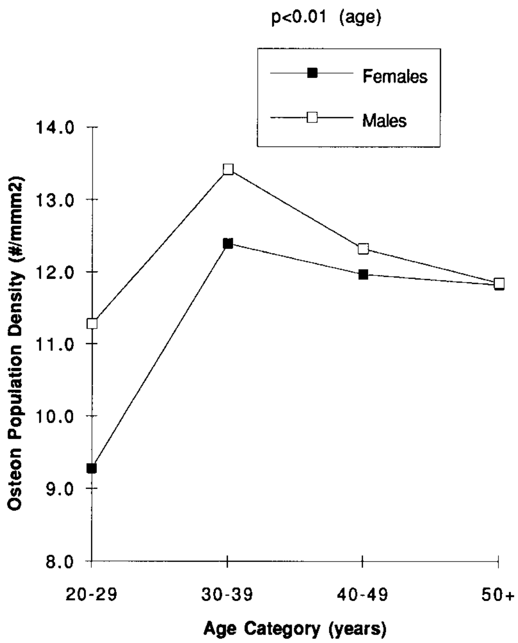

Fig. 7. Osteon population density by age category for females and males.

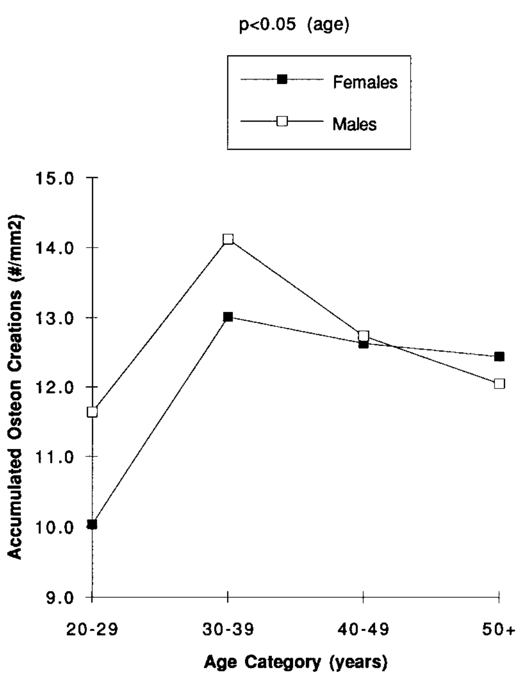

Fig. 8. Accumulated osteon creations by age category for females and males.

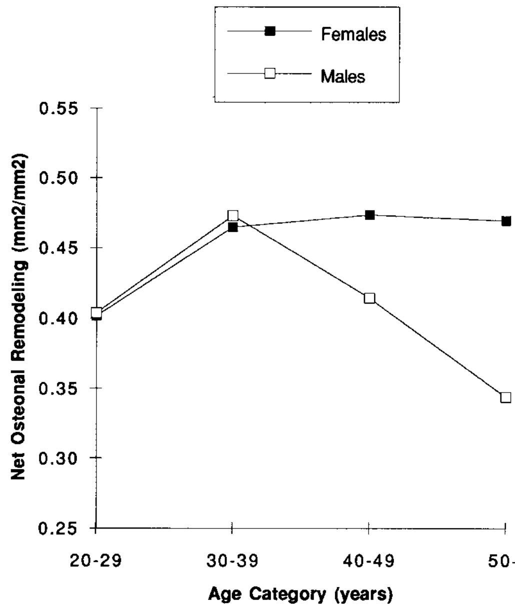

Fig. 9. Net osteonal remodeling by age category for females and males.

cally significant differences with age were found for either variable.

Sex differences

Table 4 lists the means for all variables analyzed for females, males and combined sexes. The number of intact osteons differs significantly by sex ($P < 0.0001$). The average number of intact osteons for females is significantly lower (6.73/mm^2) than males (9.74/mm^2). Further, as shown in Figure 3, males have more intact osteons at all ages than do females.

Average number of fragmentary osteons also differs significantly between the sexes ($P < 0.05$). Females have 4.68/mm^2, whereas males have 2.59/mm^2. As shown in Figure 4, females have more fragmentary osteons compared to males.

Osteon size differs significantly between males and females. Females have an average osteon area of 0.040 mm^2 and males average 0.036 mm^2. Mean osteonal cross sectional area and diameter are also significantly different between the sexes ($P < 0.05$; $P < 0.05$). Mean osteonal cross sectional area is 0.038 mm^2 for females and 0.034 mm^2 for

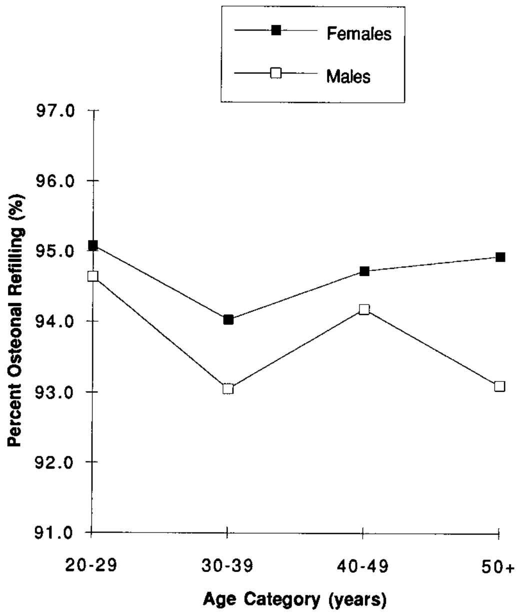

Fig. 10. Percent osteonal refilling by age category for females and males.

males. Because mean osteonal cross sectional diameter is calculated from area, similar differences are seen between males and females. Females average 0.219 mm, whereas males average 0.206 mm. As shown in Table 2 and Figure 6, females have larger mean osteonal cross sectional areas and diameters across all age categories.

Differences in osteon population density (OPD), accumulated osteon creations (AOC), net osteonal remodeling (net $V_{f,r,t}$) and percent osteonal refilling (%OR) are not different between the sexes.

DISCUSSION

Patterns of bone remodeling dynamics at Kulubnarti

Bone remodeling variables in the femora of the Kulubnarti sample reveal differences among demographic groups. Dramatic age-related increases in intact osteons, osteon population density and accumulated osteon creations were observed from the third to the fourth decades. Although these variables appear to decrease slightly during the fifth and sixth decades, differences among the fourth, fifth and sixth decades do not represent a significant decline. Therefore, age related patterns are similar to those observed for other populations (Frost and Wu, 1967; Wu et al., 1970; Stout and Teitelbaum, 1976; Stout and Lueck, 1995).

The number of intact osteons is significantly higher in males than in females, whereas the number of osteon fragments is significantly higher in females compared to males. Martin (1983) observed similar results for a sample of 363 subadult and adult femora from Wadi Halfa, Nubia, dated from 350 BC to AD 1300. She also found that males had significantly higher numbers of intact osteons than females and that females had higher (but insignificant) numbers of fragmentary osteons than males.

These results have two important implications. First, the underlying dynamics of bone remodeling exhibit a subtle difference between males and females. Females have fewer intact osteons at any given time than do males. This could be due to one or more of several factors, including the larger osteons in females, thinner cortices in females, and higher frequencies of resorption spaces in females. Prendergast-Moore (1987) observed more resorption spaces and thinner cortices in females than in males across all age categories for the same sample of femora. Also, females have increased porosity due to higher numbers of resorption spaces than in males, males have increased porosity due to higher numbers of Haversian canals.

Second, it is important to consider the number of intact and fragmentary osteons both separately and together. When the numbers of intact and fragmentary osteons are combined to calculate osteon population density, the differences observed between Kulubnarti females and males cancel out and result in similar values for accumulated osteon creations and net osteonal remodeling for both sexes. Calculating these variables without analyzing their components could mask differences in some aspects of bone remodeling dynamics. However, it is also important to realize that the frequency of intact osteons among different groups does not necessarily indicate differences in overall remodeling activity.

Kulubnarti females have significantly larger femoral osteons compared to males. Prendergast-Moore (1987) documented small

TABLE 4. Osteon counts, dimensions and calculated variables for females, males and combined sexes

Variable	Females	Males	Combined
IO (n/mm^2)	6.73 ± 0.31	9.74 ± 0.39	8.06 ± 0.33
FO (n/mm^2)	4.68 ± 0.27	2.59 ± 0.14	3.75 ± 0.23
HcA (mm^2)	0.0021 ± 0.0001	0.0022 ± 0.0002	0.0021 ± 0.0001
OA (mm^2)	0.040 ± 0.001	0.036 ± 0.002	0.038 ± 0.001
A_h (mm^2)	0.038 ± 0.001	0.034 ± 0.001	0.036 ± 0.001
D_h (mm^2)	0.219 ± 0.003	0.206 ± 0.004	0.214 ± 0.003
OPD (n/mm^2)	11.36 ± 0.43	12.31 ± 0.40	11.78 ± 0.30
AOC (n/mm^2)	12.03 ± 0.47	12.79 ± 0.43	12.36 ± 0.33
net $V_{f,r,t}$ (mm^2/mm^2)	0.452 ± 0.018	0.426 ± 0.018	0.441 ± 0.013
%OR	94.69 ± 0.23	93.91 ± 0.35	94.35 ± 0.21

Values are mean ± S.E.

osteon dimensions in a Nubian femoral sample from an early Medieval cemetery (AD 550–750) at Kulubnarti and attributed them to nutritional stress. The osteon areas observed for the present study are within the range of those observed for modern samples, however, so although males exhibited smaller osteons compared to females, the differences are unlikely nutritional in origin. The smaller osteons in males also implies less osteoclastic activity at the cellular level (Abbott et al., 1996), but bone formation and resorption were balanced in both sexes, as indicated by the percent osteonal refilling (93.9% in males and 94.7% in females).

If the differences in osteon dimensions at Kulubnarti are not due to nutritional differences, then they may be due to differences in mechanical strain (or responses to strain). If this is the case, then similar results should be found for other highly active populations.

Similar sexual differences were observed by Burr et al. (1990) for the femoral midshaft and anterior cortex in a Pecos Indian sample of 51 individuals, dating from the 14th to the 19th centuries. These researchers found significantly larger osteons in females and, like the Kulubnarti sample, significantly more intact osteons in males. They concluded that both responses increased the fatigue properties of bone, but they did not offer an explanation about why males and females would respond differently.

The sexual dimorphism observed in the Nubians and Pecos Indians may both be different solutions to similar problems. Higher numbers of intact osteons in males and larger osteons in females may both provide enhanced structural support and therefore reduce the fatigue properties of bone (Corondan and Haworth, 1986). Corondan and Haworth found that the most strain was needed to produce fractures when osteon diameters were 150 μm (with many osteons packed together) and when osteon diameters were greater than 200 μm. In the Kulubnarti sample, males have mean osteonal cross sectional diameters of 206 μm and females have diameters of 219 μm.

Stout and Lueck (1995) studied remodeling variables for three archaeological samples and one modern sample. The three archeological samples included foraging populations from the Early Archaic Windover site (6900–8120 BP) and the Middle Woodland Gibson site (50 BC–AD 400) and one agricultural sample from the Late Woodland Ledders site (AD 1000). Stout and Lueck (1995) reported no sexual dimorphism in osteon size for their archaeological samples. These studies were conducted on the rib, however, a bone that does not experience the added strain of impact-loading (like the femur), so results are consistent with a mechanical explanation for differences at Kulubnarti.

Although no data for modern samples have been reported indicating sexual dimorphism in osteon area, it is still unclear whether cultural variables are primarily responsible for the trends seen in the Nubian and Pecos samples or whether these differences are biological. One possible scenario is that Nubian and Pecos males and females performed tasks that similarly strained the femora. Different microstructural responses by each sex (higher OPD in males and larger osteon area in females)

within this context could be explained by inherent sexual differences in skeletal microstructural response to stress.

An alternative possibility is that a sexual division of labor resulted in differential strain on the femora of males compared to females. The microstructural differences could be explained in this context as different bone responses to different types of mechanical strain. Several lines of evidence support this scenario. First, Ruff et al. (1984) reported structural differences in the femur related to a sexual division of labor for three archaeological samples, including a preagricultural (2200 BC–AD 1150) and agricultural (AD 1150–1550) sample from the Georgia coast and an agricultural sample from Pecos Pueblo (AD 1300–1600). They observed differences in distribution of bone between males and females, which they attributed to a sexual division of labor where men did more hunting and women did more gathering.

Second, in modern Nubia, sexual division of labor results in different types of physical stress for males and females (Van Gerven, personal communication). Males are involved in the heavy labor associated with agricultural field preparation, whereas females maintain the fields and tend to the livestock. If today's division of labor is representative of what was going on in the past, it may explain why males and females had different responses in bone remodeling related to bone fatigue compensation.

Finally, work by Kilgore (1984) on osteophyte formation in the Kulubnarti Nubians supports a division of labor hypothesis because she found more extensive osteophyte formation in males. These results are consistent with males performing heavier labor.

Comparisons of bone remodeling dynamics at Kulubnarti with other populations

An overall assessment of bone remodeling variables also reveals differences between the Kulubnarti sample and previously published data for other skeletal samples. Haversian canal area in the Kulubnarti sample is smaller compared to modern samples studied by Currey (1964) and Thompson (1980), even though osteon area is within the range reported for modern samples (Currey, 1964; Evans, 1977). Thompson (1980) observed an age-related increase in Haversian canal size, indicating differences may partially reflect an older mean age in the modern samples. Other researchers have documented an age-related decrease in Haversian canal size, however (Singh and Gunberg, 1970). To decrease the error due to comparing samples of different ages, comparisons with the Kulubnarti sample are made including individuals 60 years at age of death and younger.

Currey's (1964) sample included femoral midshafts from 11 individuals (five females and six males) aged 60 years and younger at age of death, with a mean age of 41.9 years (only slightly higher than the Kulubnarti mean age of 37.2 years. Mean Haversian canal area (calculated from diameter) was 0.0045 mm^2, significantly larger ($P < 0.001$) than the Kulubnarti mean of 0.0021 mm^2.

Thompson (1980) studied the anterior femoral midshafts from 11 individuals (four males and seven females) aged 50–59 years at age of death. He found that males had a mean Haversian canal area of 0.0041 mm^2 and females had a mean area of 0.0063 mm^2, both significantly larger ($P < 0.001$; $P < 0.001$) than Haversian canals observed for the Kulubnarti sample.

Burr et al. (1990) also observed small mean Haversian canal areas (0.0023 mm^2 in males and 0.0024 mm^2 in females) relative to modern samples in their study of Pecos Indian skeletal remains. These researchers attributed differences partially to a younger age at death in their sample, but they also noted that the difference may indicate a greater volume of bone per unit area (since osteon areas were in the range of modern values), a feature consistent with the active lifestyle of the population. Small Haversian canals at Kulubnarti provide compelling evidence for this conclusion because they are also associated with osteon sizes in the modern range and the people of Kulubnarti also experienced a high degree of mechanical strain.

Net remodeling in the femora at Kulubnarti is higher than net remodeling observed in two samples of fossil hominids studied by Abbott et al. (1996). The Kulubnarti femora had a mean value of 0.441 mm^2/mm^2, whereas seven Late Archaic individuals and

three Early Modern individuals had net remodeling values of 0.37 mm^2/mm^2 and 0.22 mm^2/mm^2, respectively. The Kulubnarti sample was significantly different from the Early Modern group ($P < 0.001$), but due to the rarity of fossil remains, sample sizes are too small to be conclusive about statistical significance. Lower net remodeling values in the Late Archaic and Early Modern samples may reflect comparatively higher mechanical strain in these early groups compared to the Kulubnarti sample, because the Mechanostat Theory predicts that rates of bone remodeling will be lower for bones experiencing mechanical strain that exceeds the minimum effective strain for that bone (Frost, 1987b).

No data are available for comparisons of femoral net remodeling with modern samples, but Stout and Lueck (1995) report a mean value of 0.937 mm^2/mm^2 in a sample of 45 ribs, a value significantly higher ($P < 0.001$) compared to the Kulubnarti sample. The mean age at death for the modern sample was 34.9, compared to the Kulubnarti mean age of 37.2 years, so higher net remodeling in the modern sample is not due to a higher mean age. Comparisons between bones are problematic, however. For example, the effective age of the adult compacta is likely higher in the femur compared to the rib. Because the femur has more mechanical demands than the rib, more factors influence cortical drift during childhood, potentially lengthening the period of rapid bone modeling. This would result in lower osteon population densities, accumulated osteon creations and, therefore, lower net remodeling in the femur (for age-matched samples) because secondary osteons accumulated over a shorter period of time.

CONCLUSIONS

Microscopic changes in femoral cortical bone were observed with age and sex for a Medieval population from Kulubnarti, Nubia. Results of this study were examined in the light of previous archaeological, skeletal and ethnographic research and compared with results from other studies to determine whether age, sex and activity pattern affect histomorphometry.

Evaluation of bone remodeling variables for femoral samples from a Medieval Nubian population reveals several demographic differences, including those by age and sex. Aging patterns are similar to those observed for other samples, as the number of intact osteons increases (and, in this case then decreases slightly) and number of fragmentary osteons and resorption spaces increases.

Differences between the sexes in intact osteon density and osteon size indicate that males and females may have experienced different types of mechanical strain. Males responded by building more intact osteons, whereas females respond by building larger osteons. Observed differences in remodeling variables may reflect differences in activity pattern where males were involved in heavy labor and females performed more time-consuming duties associated with subsistence. These results indicate that evidence about differences in activity pattern within populations may be detectable in the organization of bone tissue.

Comparisons with modern skeletal samples show that the Kulubnarti Nubians had small Haversian canals compared to modern samples, resulting in higher bone volume per osteon. Overall, these findings are consistent with a population experiencing a physically active lifestyle.

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LITERATURE CITED

Abbott S, Trinkaus E, and Burr DB (1996) Dynamic bone remodeling in later Pleistocene fossil hominids. Am. J. Phys. Anthropol. *99:*585–601.

Adams WY (1977) Nubia: Corridor to Africa. Princeton: Princeton University Press.

Ahlquist J and Damsten O (1969) A modification of Kerley's method for the microscopic determination of age in human bone. J. Forensic Sci. *14:*205–212.

Bartley MH and Arnold JS (1967) Sex differences in human skeletal involution. Nature *214:*908–909.

Burr DB, Ruff CB, and Thompson DD (1990) Patterns of skeletal histologic change through time: Comparison

of an archaic Native American population with modern populations. Anat. Rec. *226:*307–313.
Burrell LL, Mass MC, and Van Gerven DP (1986) Patterns of long-bone fracture in two Nubian cemeteries. Hum. Evol. *1:*495–506.
Corondan G and Haworth WL (1986) A fractographic study of human long bone. J. Biomech. *19:*207–218.
Currey JD (1964) Some effects of ageing in human Haversian systems. J. Anat. *98:*69–75.
Dewey JR, Armelagos GJ, and Bartley MH (1969) Femoral cortical involution in three Nubian archaeological populations. Hum. Biol. *41:*13–28.
Eriksen MF (1991) Histologic estimation of age at death using the anterior cortex of the femur. Am. J. Phys. Anthropol. *84:*171–179.
Evans FG (1977) Age changes in mechanical properties and histology of human compact bone. Yrbk. Phys. Anthropol. *20:*57–72.
Frost HM (1987a) Secondary osteon population densities: an algorithm for estimating the missing osteons. Yrbk. Phys. Anthropol. *30:*239–254.
Frost HM (1987b) Bone "mass" and the "mechanostat": A proposal. Anat. Rec. *219:*1–9.
Frost HM and Wu K (1967) Histological measurements of bone formation rates in contemporary archaeological and paleontological compact bone. In WD Woode (ed): Miscellaneous Papers in Paleopathology. Flagstaff: Museum of Northern Arizona, pp. 9–22.
Galai (1991) Cue-2 Olympus Image Analyzer Software.
Greene DL, Ewing G, and Armelagos GJ (1967) Dentition of a Mesolithic population from Wadi Halfa, Sudan. Am. J. Phys. Anthropol. *60:*471–478.
Kerley ER (1965) The microscopic determination of age in human bone. Am. J. Phys. Anthropol. *23:*149–164.
Kilgore L (1984) Degenerative joint disease in a Medieval Nubian Population. Ph.D. dissertation. University of Colorado, Boulder, CO.
Kilgore L, Jurmain R, and Van Gerven DP (in press) Patterns of trauma in a Medieval Nubian skeletal population. Int. J. Osteoarchaeol.
Martin DL (1983) Paleophysiological aspects of bone remodeling in the Meroitic, X-Group and Christian populations from Sudanese Nubia. Ph.D. dissertation. University of Massachusetts, Amherst, MA.
Martin DL and Armelagos GJ (1979) Morphometrics of compact bone: An example from Sudanese Nubia. Am. J. Phys. Anthropol. *51:*571–578.
Martin RB and Burr DB (1989) Structure, Function and Adaptation of Compact Bone. New York: Raven.
Prendergast-Moore K (1987) Osteopenia in a medieval population from Kulubnarti, Sudan. Ph.D. dissertation. University of Colorado, Boulder, CO.
Ruff CB, Larsen CS, and Hayes WC (1984) Structural changes in the femur with the transition to agriculture on the Georgia coast. Am. J. Phys. Anthropol. *64:*125–136.
Singh IJ and Gunberg DL (1970) Estimation of age at death in human males from quantitative histology of bone fragments. Am. J. Phys. Anthropol. *33:*373–381.
Stout SD (1978) Histological structure and its preservation in ancient bone. Curr. Anthro. *19:*601–603.
Stout SD and Lueck R (1995) Bone remodeling rates and skeletal maturation in three archaeological skeletal populations. Am. J. Phys. Anthropol. *98:*600–604.
Stout SD and Paine RR (1994) Brief communication: bone remodeling rates: A test of an algorithm for estimating missing osteons. Am. J. Phys. Anthropol. *93:*123–129.
Stout SD and Teitelbaum SL (1976) Histomorphometric determination of formation rates of archaeological bone. Calcif. Tissue Res. *21:*163–169.
Thompson DD (1980) Age changes in bone mineralization, cortical thickness and Haversian canal area. Calcif. Tissue. Int. *31:*5–11.
Van Gerven DP, Sanford MK, and Hummert JR (1981) Mortality and culture change in Nubia's Batn el Hajar. J. Hum. Evol. *10:*395–408.
Van Gerven DP, Hummert JR, Prendergast-Moore K, and Sanford MK (1990) Nutrition, disease, and the human life cycle: A bioethnography of a medieval Nubian community. In J DeRousseau (ed.): Primate Life History and Evolution. New York: Wiley-Liss, pp. 297–323.
Wu K, Schubeck KE, Frost HM, and Villaneuva A (1970) Haversian bone formation rates determined by a new method in a mastadon and in human diabetes mellitus and osteoporosis. Calcif. Tissue Res. *6:*204–219.